Design and Development of Intelligent Footwear for Fitness Applications

Synopsis

Submitted in the partial fulfilment for the requirement of

Doctor of Philosophy

in

FOOTWEAR TECHNOLOGY

Submitted by
NISHA VERMA

Under the Supervision of
PROF. D. K. Chaturvedi

Department of Footwear Technology, Faculty of Engineering
Dayalbagh Educational Institute (Deemed to be University)
Dayalbagh, Agra - 282 005
2025

Abstract

The acquisition of raw materials (RAM), product design and manufacture (DMA), transportation, and marketing are all being fundamentally altered by machine intelligence and its learning (MIL). The consumer goods business, which includes the smart footwear sector, has been greatly impacted by MIL. Craftsmanship has given way to mass production, mass production to customization, and customization to mass customization in the footwear industry. Using augmented and virtual reality (AVR), MIL is widely used in the design and manufacturing of intelligent and nimble footwear. Smart footwear can be made in a variety of ways and classed according to its intended use.

The proposed intelligent footwear will collect parameters/data from different sensors/IoTs installed in footwear and will use these parameters/data to suggest different activities for physical and mental well-being. This will also assist people for their betterment. **Introduction**

Any transformation in a society is mostly determined by its literacy level. People with a high literacy level are more concerned about their health and strive to maintain a healthy appearance. It leads to an increase in the demand for various types of smart and intelligent shoes. It not only measures your health factors such as blood pressure, oxygen level, diabetes level, calorie intake and burn, and so on, but it also provides advice on how to stay fit and healthy. The local sports shoe market in India is dominated by four multinational brands: REEBOK, ADIDAS, PUMA, and Nike. These companies are actively involved in the manufacturing of smart shoes. Nike has a technological relationship with Intel, a chip manufacturing business, to embed intelligence into shoes. There is a paradigm shift from traditional mass-production to customer-centered tailored production to meet lifestyle, fashion, and, most importantly, physical and mental health and comfort. The integration of electronic and mechanical components, controllers, and microprocessors has transformed the shoe into a smart footwear. Smart footwear offers personalized cell phone apps for self-monitoring the different activities and suggest many useful solutions. Smart shoe is capable of recording and monitoring daily activities. Using intelligent sensors/IoTs allows footwear to function as an SF. Sensors/IoTs can monitor daily activities and provide crucial information such as foot pressure points, posture, fatigue level, footwear temperature, sweating, step count, weight, and location.

Literature Review

Modern industries are operating entirely different than conventional industries due artificial machine intelligence and learning (MIL), starting with the procurement of raw materials (RAM), product design and manufacture (DMA), transportation, and marketing. The market for consumer goods, especially the smart footwear sector, has been greatly impacted by MIL. The production of shoes has seen significant transformation, moving from artisan to mass production, then from mass production to customization, and finally from customization to mass customization. MIL is widely used in the development and manufacturing of augmented and virtual reality (AVR)-based smart and agile footwear. Based on its intended use, smart footwear can be manufactured using a variety of techniques. These include, among other things, smart footwear for medical and healthcare purposes, assistive footwear for people (Blind people shoe, anti-falling shoes, GPS smart shoe for old age people having problem of dementia), footwear for gait analysis and foot movement research, safety footwear, anti-skid footwear, shoes army personals, and energy-harvesting footwear. Real-time patient monitoring is made possible by these smart sneakers [ABD 24], which also offer pertinent treatment recommendations. Furthermore, the equipment and methods utilized in the manufacturing process, the sensors employed by IoTs, data transfer, and storage can all be used to categorize smart footwear. The diverse tools and methods utilized to create smart footwear for various applications are reviewed in this study [WAN 18] . The many kinds of sensors/IoTs utilized in smart footwear are also covered.

According to WHO 422 Million people have diabetes and 1.6 million deaths are directly attributed to diabetes every year. A great risk to diabetes which could be the 7th leading cause of death in the world by 20303 [W-1].

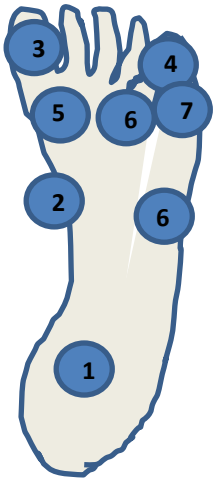
In addition, the cardiovascular diseases (CVDs) according to WHO take the lives of 17.7 million people every year, 31% of all global deaths. Triggering these diseases – which manifest primarily as heart attacks and strokes – are tobacco use, unhealthy diet, physical inactivity and the harmful use of alcohol.

Hence, there is a genuine need for intelligent footwear which will take care of physical fitness of the wearer. There are many dimensions of physical fitness. Some important dimensions are mentioned below:

1. Cardiovascular Endurance (CVE): CVE is the ability of heart, lungs and blood vessels to deliver oxygen to different body tissues during different physical activities such as walking, jumping, running, cycling etc. it is basically express the stamina of an individual.
2. Muscles endurance and strength – muscles endurance is the ability to repeatedly apply force do something. Muscle strength is the amount of force applied against resistance.
3. Flexibility – This deals with the joints flexibility under different activities like exercises.
4. Body Mass index (BMI) - It reflects the fat of the body.
5. Coordination – It is related to the balance and stability of body.

To monitor these dimensions for physical fitness different sensors/IoTs will used.

Salma Saidani et.al. [**[SAI18]**] mentioned the smart insole which uses sensors/IoTs at different points of shoe insole as shown in Fig. 1.



1 – Heel

2 – Media Mid foot

3 – Great Toe

4 – Lesser Toe

5, 6, 7 – Meta tarsals

Fig. 1 Different Sensors/IoTs points on smart insole

The Smart shoe comprises a low-cost sensors/Iots in insole and application software on both smartphone and personal computer for data storage, processing and visualization. The insole consists of an array of sensors, an ultra-low power micro control unit (MCU) and Bluetooth low energy (BLE) wireless communication module, a channel multiplexer (MUX), a battery, and a micro-Universal Serial Bus (USB) connector module. The application software provides visualization and a real-time guided feedback to the user. The data stored in Secure Digital (SD) card will be used to study lifestyle and health behaviors that facilitate new understanding and effective intervention options to promote individual independence.

Smart shoe can measure:

a. Assistive shoes: step counts, step pace, swing time, and center of pressure (COP) shifting velocity, which can further infer the walking balance status and potential fall risk in real life [LEE 22], GPS module for tracking for old age people/kids [Fox 05], sonar sensor based blind people assistance shoes [NAN 21].

b. Medical or health care shoes: measure BP, Diabatic level, Oxygen Level, hear beat, body temperature, body sweating, overweight and obesity. It can also measure physical activity contributes to weight loss and improved blood pressure and lipid profile [SOG 06]. Walking has the primary role in both primary and secondary prevention of CVD. Thirty minutes of walking per day reduces the risk of coronary heart disease by 19% [BPA 15, LFW 15]. If a person should perform excise by undertaking 3000 steps during 30 min to feel warm and to sweat lightly [XLZ 11, WIL 13]. In fact, obesity is associated with diabetes and cardiovascular disease, however obesity is also associated with musculoskeletal disorders affecting the lower limb, such as knee and hip osteoarthritis. [AND 21]. As per WHO, By 2030, the number of overweight people is expected to reach 3.3 billion [FIN 12, KEL 08]. The intelligent shoe measures most of the human parameters/activities without disturbing the quality lifestyle of the subject.

c. Defense shoes: Auto-lighting, power generated shoe, identify land mines, etc.

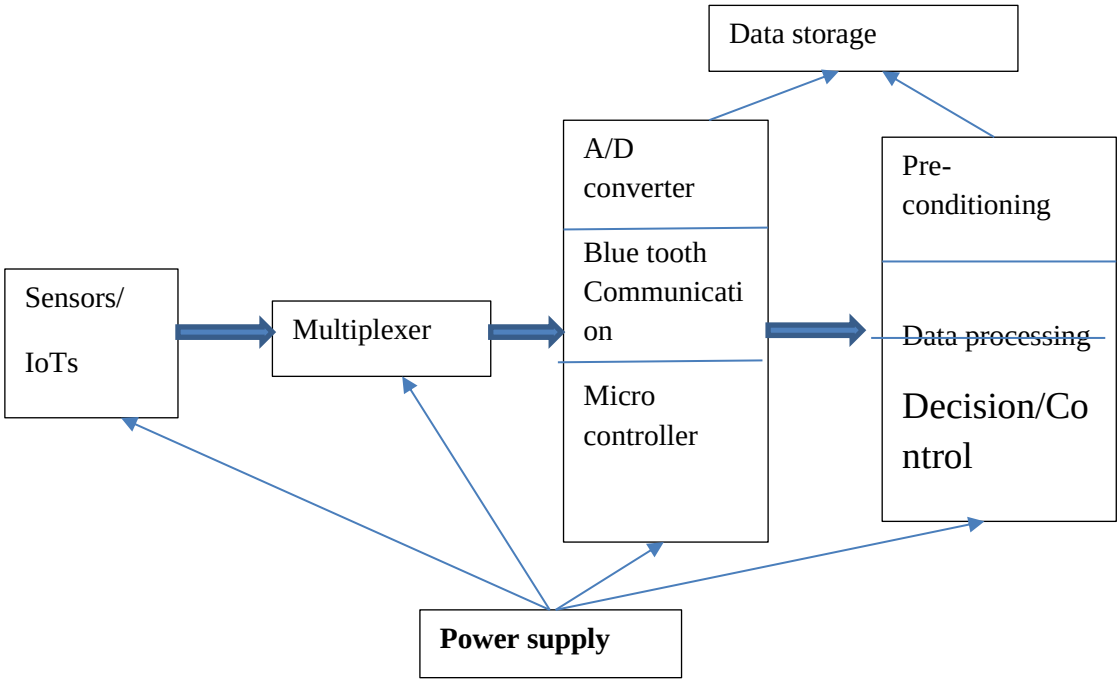


Fig. 2 Design of smart shoe insole

There are numerous sensors/IoTs available in the market. Each one has its own merits and demerits based on power consumption, weight, size, their working principles, sensitivity, response time and accuracy. Some of the sensors/IoTs used in smart shoes are mentioned in Table 1.

Table 1 Sensors/IoTs Employed in Smart Footwear

Quantity to measure	Sensor/IoT	How to measure
1. Foot Pressure	Force Sensor Resistor (FSR)	physical pressure and weight distribution and magnitude
	Capacitive sensor (CS)	Measure change in capacitance due to pressure applied
	Piezo-electric sensor (PES)	Generate electric charge when pressure applied
	Piezo-resistance sensor (PRS)	Resistance change due to applied pressure
	Load cell	Measure force and weight distribution
	Strain gauge	To measure deformation due to pressure
	Pressure Sensitive Conductive Rubber (PSCR)	Changes conductivity when pressure applied.
	Flexible sensor	Thin and flexible sensors that can't discomfort to foot.
	Micro-Electro-Mechanical sensor (MEMS)	Tiny sensor to measure pressure and acceleration
	Optical sensors	To measure pressure-induced changes
	Ultrasonic sensors	It uses high frequency sound waves to measure pressure.
	Resistive sensor	To measure changes in resistance due to pressure.
2 – Heart activity (Heart rate, its variability, R-R interval, Blood oxygen level), cardiac output, stroke volume)	ECG sensor	measure the electrical activity of the heart
	Photo plethysmography (PPG)	Detect change in blood flow and oxygenation.
	Ballisto-cardiogram (BCG)	Measure mechanical movement of the heart
	Seismo-cardiogram (SCG)	Detect the vibrations produced by heart
	Impedance-cardiogram (ICG)	Measure changes in electrical impedance due to heart activity
	PES	Detect the mechanical movement of heart.
	Capacitive sensor	Measure change in capacitance due to heart activity.
	Bio-impedance sensor	Measure electrical impedance of body
3 - Measure orientation, acceleration, rotation and the inclination of the foot	Mechanical Gyroscope	Uses spinning wheel or rotor to detect changes in orientation.
	Optical Gyroscope	Uses light to measure changes in orientation and rotation
	MEMS Gyroscopes	Tiny, low power sensors to detect changes in orientation and rotation
	Piezo-electric Gyroscopes	Use piezo-electric material to detect changes in orientation and rotation.
	Vibrating structure Gyroscopes	Uses vibrating elements to detect changes in orientation and rotation.
	Laser Gyroscopes	Uses laser light to measure changes in orientation and rotation.
	Fiber optic Gyroscopes	Uses fiber optic cables to detect changes in

		orientation and rotation.
	Quartz crystal Gyroscopes	Uses quartz crystal to detect changes in orientation and rotation.
	Solid state Gyroscopes	Uses solid state sensors to detect changes in orientation and rotation.
	3-axis Gyroscopes	Measure movements and orientations in 3-D.
4- To measure acceleration of the foot, allowing the smart footwear to detect steps, pace and distance.	Piezo-electric Accelerometer	Use piezo-electric material to detect changes in acceleration
	Capacitive accelerometer	Measure changes in capacitance due to acceleration
	Piezo-resistive accelerometer	Use piezo-resistive material to detect changes in acceleration
	MEMS Accelerometer	Low Power sensor to detect acceleration
	Strain gauge accelerometer	Measure change in strain due to acceleration.
	Quartz Crystal accelerometer	Use quartz crystal to detect changes in acceleration
	Surface Acoustic Wave (SAW) accelerometer	Use surface acoustic waves to detect changes in acceleration
	Optical accelerometer	Uses light to measure changes in acceleration.
	Inertial measurement Unit (IMU) accelerometer	Combine multiple sensors to measure acceleration, orientation and rotation.
	3-axis accelerometer	Measure acceleration in 3-D
5 – location and tracking	GPS	Provide location, track distance, pace and route.
6 - Temperature	Thermistor	Resistive sensor changes resistance with temperature.
	Thermocouple	Generate voltage proportional to temperature
	IR sensor	Measure thermal radiation to detect temperature
	Thermopiles	Uses multiple thermos couples to detect temperature
	RTDs	Measure changes in resistance due to temperature
	Thermistor based sensor	Use thermistors to detect temperature
	MEMS	Small size sensor to measure temperature
	Fiber optic temperature sensor	Uses fiber optic cables to measure temperature
	Piezo-electric	Use piezo – electric materials to detect temperature
	Calorimetric sensor	Measure heat transfer to detect temperature
7- Measurement of sweat rate, its composition, Electrolyte level, hydration level, stress level, physical exertion, and heat stress	Electro-dermal activity (EDA) sensor	Measure electrical conductivity of sweat.
	Galvanic Skin Resistance (GSR) sensor	Measure change in skin conductivity due to sweat.
	Capacitive sensor	Measure change in capacitance due to sweat.
	Resistive sensor	Measure change in resistance due to sweat.
	Hygrometer	Measuring relative humidity, including sweat levels
	pH sensor	Detect change in skin pH due to sweat
	Conductive sensor	Measure electrical conductivity of sweat
	Impedance sensor	Measure change in impedance due to sweat
	Optical sensor	Uses light absorbance or reflectance due to sweat

	Bio-impedance sensor	Measure change in skin impedance due to sweat.
8-Measurement of BP, Pulse transit time, Pulse wave velocity, oxygen level	Piezo – electric sensor	Measure change in pressure
	Capacitive sensor	Measure change in capacitance due to blood flow
	Resistive sensor	Measure change in resistance due to blood flow
	Optical sensor	Use light for detecting blood flow
	Bio-impedance sensor	Measure impedance change due to blood flow
	BCG sensor	Measure mechanical movement of the heart
	SCG sensor	Detect vibrations produced by heart.
	PPG sensors	Measure change in light absorption due to blood flow

Some of the most commonly used sensors for insole systems of smart shoes are mentioned in Table – 2.

Table 2 Different Sensors for Insole Systems of Smart Shoes

Insole	Sensor Type	Number of Sensors	Battery Life time	Communication
F-scan [SCS 16]	Resistive	960	2 hours	USB
Dynafoot [DTF 18]	Resistive Accelerometer	58	3.5 hours	Bluetooth
Wisel [ALM 22]	Resistive Accelerometer Gyroscope	14	NA	Bluetooth
Moticon [RAH 12]	Capacitive 3D Accelerometer	13	NA	Wireless
Pedar-X Insole [ALM 22]	Piezo electric	99	4-5 hours	Bluetooth USB Optical fiber
Orpyx LogR	NA	8	8-12 hours	Bluetooth
Footwork Insole [CHA 24]	Capacitive	80	3 hours	Bluetooth USB
Medilogic Insole[LID 19]	NA	240	16 hours	Wireless
Biofoot[MAR 07]	Piezo-electric	64	NA	WiFi USB
Paro-tech [SAI 18]	Piezo Resistive Hydro cell	24 to 36	NA	SD card
Sensor Medica Flexinfit [SAI 18]	Resistive	214	4 hours	Bluetooth
SennoproInsole X[SAI 18]	Textile sensors accelerometer Gyroscope	48	48 hours	Bluetooth
Digit sole [SAT 17]	NA	NA	7/8 hours	Bluetooth USB
Arion smart insole [SA 18]	Accelerometer, Gyroscope and GPS	8	7 hours	Bluetooth

4. Data processing and information extraction: The data is pre-processed before using it. Mainly in pre-processing of data, the missing data is completed or removed, remove noise from the data, and also check the erroneous data. The pre-processed data is then used for information/feature extraction.

5. Data Analysis: Different soft computing techniques such as neural network, fuzzy information processing system, optimization based on nature inspired techniques, etc. are used to analyse the pre-processed collected data for some interfacing.

6. Decision making: The appropriate decision is to be taken based on the analysis.

7. Control Once the appropriate decision has been taken using some intelligent tools, then suitable control action is initiated.

8. Learning Mechanism – Neural network may be used for learning to make the system adaptable.

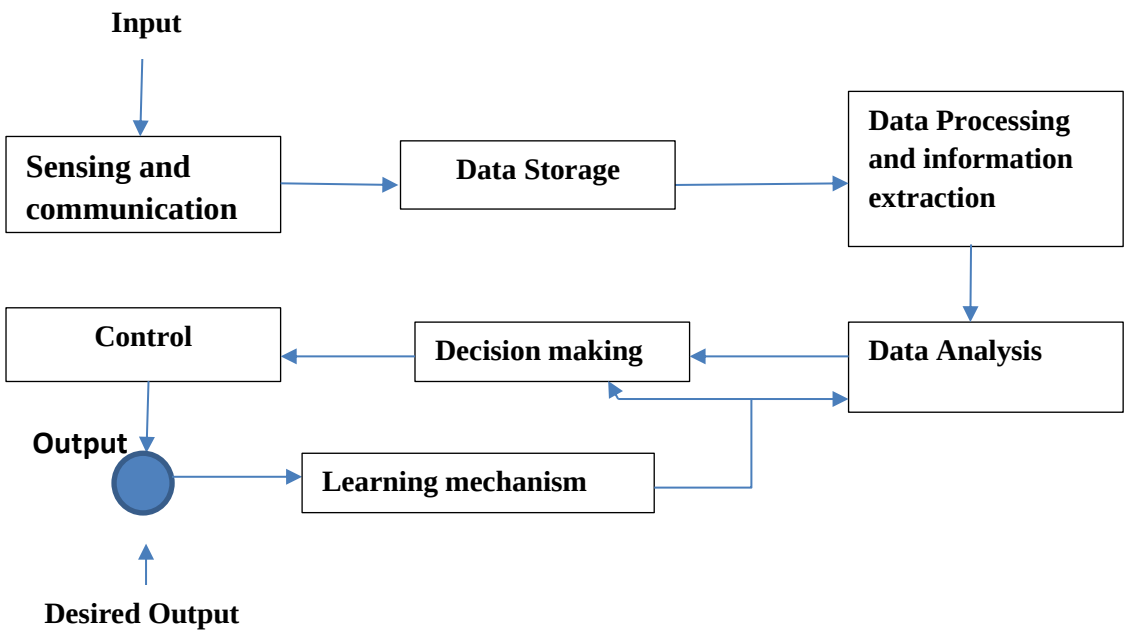


Fig. 3 Block Diagram of Proposed Intelligent Footwear

Different components of Smart footwear:

1) Smart Footwear has many components depending on their applications, but some commonly used components (Fig. 6) are mentioned below:
2) Sensors/IoTs – To measure different variables such as pressure, temperature, humidity, acceleration, speed, location etc. There are variety of sensors/IoTs available in the market based on their cost, accuracy, range, shape and size, working principle etc.
3) Micro-controllers- To process data obtained from sensors/IoTs and control other components.

4) Storage Module – To store data received from sensors/IoTs, suitable place and fast memory is needed. It also needs suitable transmission channel and software.

5) Communication module – it enables connectivity of smart footwear to smart phones, smart home devices or other systems via blue tooth, wi-Fi, or NFC.

6) Power supply module: Battery, charging (through USB, wireless or other charging methods such as energy harvesting devices) and discharging circuitry, battery management system.

7) User Interface – Display of results, buttons or touch sensors for user interface.

8) Footwear Material to protect electronic circuits.

9) Software and applications – It is required for data analysis, feedback and customization.

10) Integration module - Integration with other devices and its compatibility. Actuators, motors, alert systems and other safety mechanism.

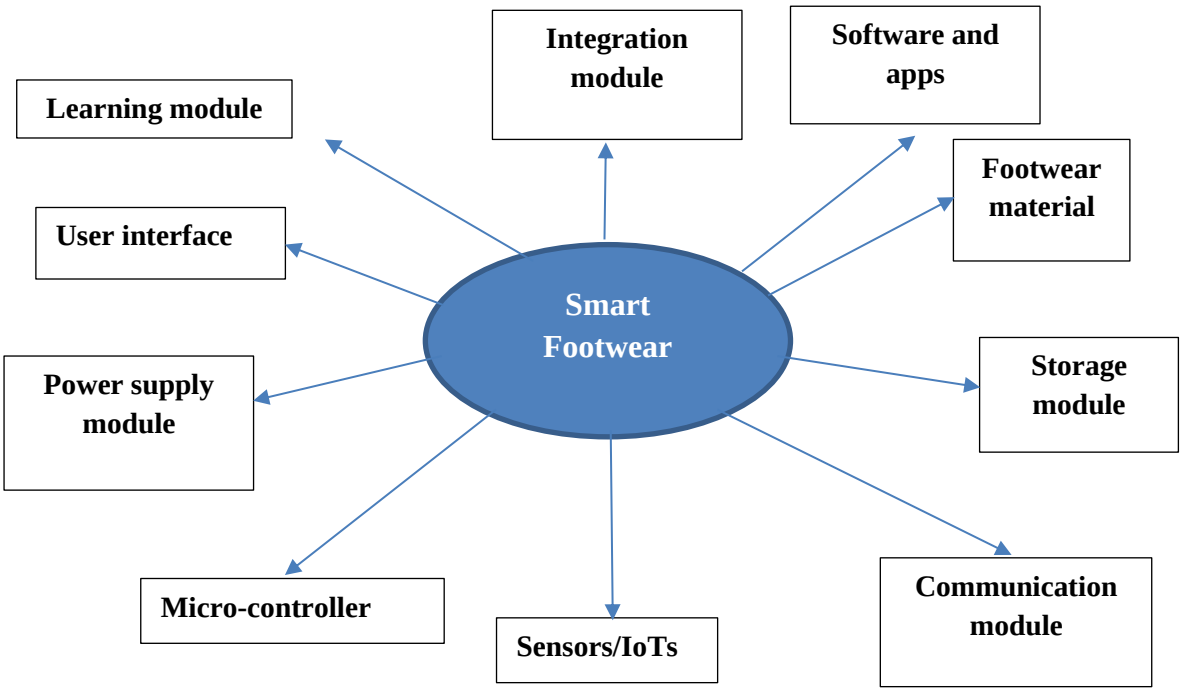


Fig. 4 Components of Proposed Intelligent Footwear System

Applications of Smart Footwear

Smart footwear is used in the following areas [SAI 18]:

Games and Sports– Smart footwear is very commonly used in sports and games to enhance the players' performance [7-9].

Fitness of an individual – It is used in different fitness activities such as walking, running, jogging, cycling or doing exercise.

Health care and Medical – It is used for diagnosis of different disease or abnormality in the body. It is also used to maintain the history of different bio-physical parameters of an individual. Smart footwear for diabetes and rehabilitation [ABD 24].

Industrial and work safety- This is also a prominent area where smart footwear is used to protect the industrial worker from hazardous environment or any safety issue.

Women and kids safety – To safeguard women and kids from any unforeseen situation

1) Gaming and virtual reality, 2) Fashion and life style, 3) Assistive footwear for blind persons , 4) Army shoes

Smart shoe manufacturing and its challenges are given as under

1) Selection of suitable sensors, 2) Sensor accuracy and its reliability, 3) Power consumption and battery life, 4) Self-powered sensors, 5) Comfort and wear ability, 6) Durability and water resistance 7) Data transmission, storage and analysis and feedback mechanisms, 8) Suitable tools and techniques for decision making and control, 9) Integration with other devices and systems

Research gaps:

- The following research gaps have been identified based on the literature review:
- Reduction of power consumption - In smart shoe the battery consumption is a major issue. Every component of smart shoe needs power, which requires frequent charging of batteries. No work is done in these lines.
- Selection of optimal number of sensors - It is a crucial factor and decided based on their working principle, type, weight and size.
- Reliability and robustness- Smart footwear must withstand with environmental conditions- dust, dirt, water, mud, humidity and temperature variations, etc.
- High cost of smart footwear.
- No research available on smart footwear which deals with physical and mental well- being.

PROBLEM STATEMENT

To design and develop intelligent footwear to improve fitness for physical well-being.

OBJECTIVES

1. To design and develop self -power generating insole of footwear.
2. Identifying the important features of proposed intelligent footwear.
3. Selection of different sensors and their locations on insole of intelligent footwear.
4. To design a suitable hardware/software architecture for intelligent footwear.
5. To develop a low cost intelligent footwear for fitness applications.

The tentative schedule for different objectives are also shown in Fig. 5.

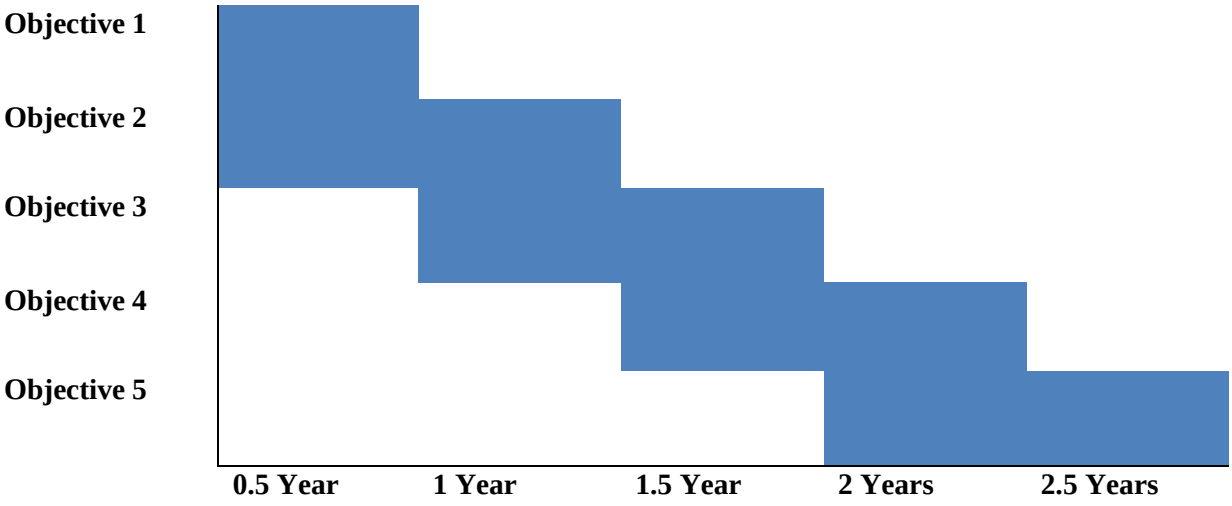


Fig. 5 Tentative Plan

Methodology

In the beginning, the literature survey on smart footwear will be done by studying the national and international journals, research and review paper. This must be achieved to know about the present state of art in this area. After thorough literature review, the research gaps will be identified precisely and work upon these gaps. In next phase, intelligent shoe will be developed which will generate the power for different applications. Then, important features of intelligent shoe will be identified and based on that sensors will be selected. The suitable architecture is designed and implemented on the bread board and validated the functioning of smart features. Finally design and develop the intelligent shoe for fitness applications. The design and development of smart shoe shall be completed as shown in flow chart (Fig. 6).

Work Flow

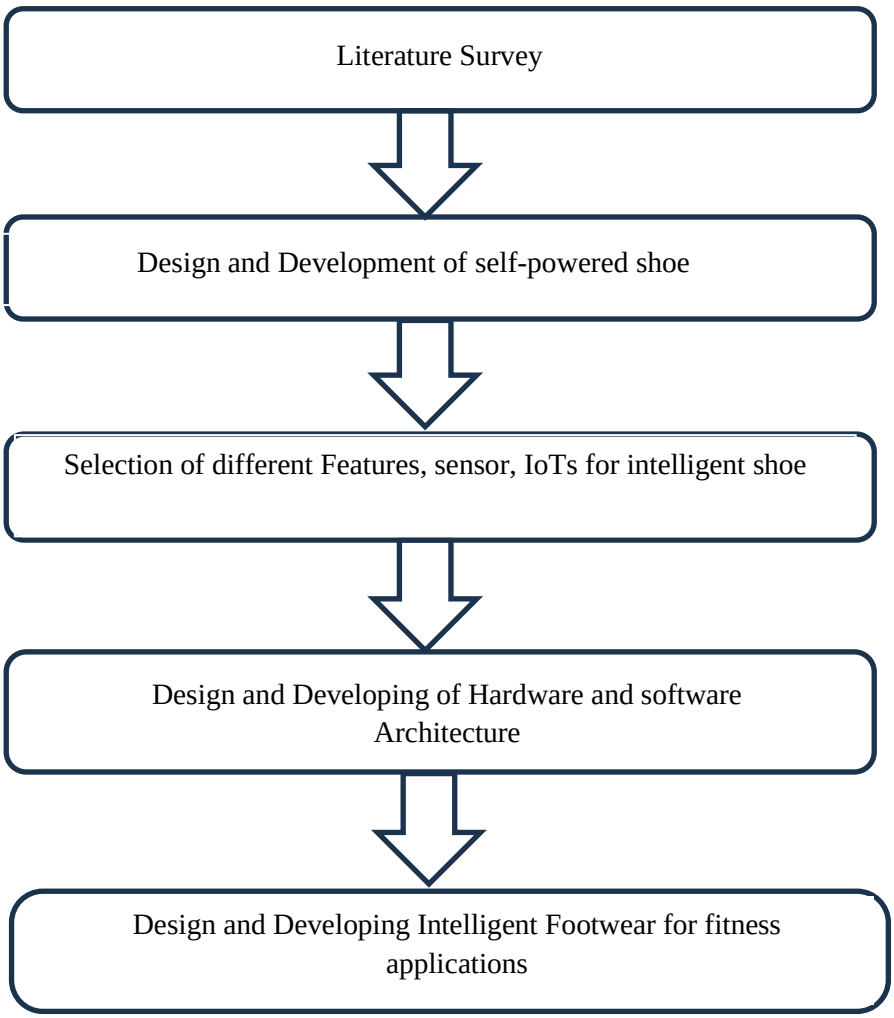

Literature Survey
Design and Development of self-powered shoe
Selection of different Features, sensor, IoTs for intelligent shoe
Design and Developing of Hardware and software Architecture
Design and Developing Intelligent Footwear for fitness applications

Fig. 6 Flow Chart

References:

[ABD 24] Abdollahi, M., Zhou, Q., & Yuan, W. (2024). Smart wearable insoles in industrial environments: A systematic review. Applied Ergonomics, 118, 104250.

[ABU 15] amcube, Berkshire, U.K. ―In-shoe pressure measurement | mobile foot pressure measurement,‖ In-Shoe Pressure Measurement Mobile & Practical.2015.Available:http://www.amcube.co.uk/products/inshoepressure-measurement/.

[ALM 22] Almuteb, I., Hua, R., & Wang, Y. (2022). Smart insoles review (2008-2021): Applications, potentials, and future. Smart Health, 25, 100301..

[AND 21] Anderson, J., Williams, A. E., & Nester, C. (2021). Musculoskeletal disorders, foot health

and footwear choice in occupations involving prolonged standing. *International Journal of Industrial Ergonomics*, *81*, 103079.

[BPA 15] Butterworth, P. A., Urquhart, D. M., Landorf, K. B., Wluka, A. E., Cicuttini, F. M., & Menz, H. B. (2015). Foot posture, range of motion and plantar pressure characteristics in obese and non-obese individuals. Gait & posture, 41(2).

[CHA 24] D.K. Chaturvedi, Nisha Verma, "Smart Footwear: A Review", Indian Leather Technologists' Association (JILTA), Dec. 2024, Vol.LXXV, issue 12, pp.17-22.

[FIN 12] Finkelstein, E. A., Khavjou, O. A., Thompson, H., Trogdon, J. G., Pan, L., Sherry, B., & Dietz, W. (2012). Obesity and severe obesity forecasts through 2030. *American journal of preventive medicine*, *42*(6), 563-570.

[HEX 12] Hex, N.; Bartlett, C.; Wright, D.; Taylor, M.; Varley, D. (2012) Estimating the current and future costs of Type 1 and Type 2 diabetes in the UK, including direct health costs and indirect societal and productivity costs. Diabet. Med. 29, 855–862.

[KEL 08] Kelly, T., Yang, W., Chen, C. S., Reynolds, K., & He, J. (2008). Global burden of obesity in 2005 and projections to 2030. *International journal of obesity*, *32*(9), 1431-1437.

[KGA 2003] Kelley G A, Kelley K S and Tran Z V (2003) Walking and non- HDL-C in adults: a meta-analysis of randomized controlled n trials Prev Cardiol. 8 102–7.

[LEE 22] Lee, Y. C., Chang, S. F., Kao, C. Y., & Tsai, H. C. (2022). Muscle strength, physical fitness, balance, and walking ability at risk of fall for prefrail older people. *BioMed research international*, *2022*(1), 4581126.

[LFW 15] Lin, F., Wang, A., Song, C., Xu, W., Li, Z., & Li, Q. (2015, December). A comparative study of smart insole on real-world step count. In 2015 IEEE Signal Processing in Medicine and Biology Symposium (SPMB) (pp. 1-6). IEEE.

[LVR 2004] Lavery, L. A., Higgins, K. R., Lanctot, D. R., Constantinides, G. P., Zamorano, R. G., Armstrong, D. G., ... & Agrawal, C. M. (2004). Home monitoring of foot skin temperatures to prevent ulceration. Diabetes care, 27(11), 2642-2647

[MEM 10] Murtagh, E. M., Murphy, M. H., & Boone-Heinonen, J. (2010). Walking: the first steps in cardiovascular disease prevention. *Current opinion in cardiology*, *25*(5), 490-496

[MSO 16] medilogic, Sch¨onefeld,Germany, ―Medilogic insole science.‖ 2016. Available: http://www.medilogic.com/en/products-human/foot pressure measurement/medilogic-insole/.

[NAN 21] Nandalal, V., Kumar, V. A., Sujitha, A., Sumitha, G., & Sureka, A. S. (2021, October). Intelligent multi-utility shoe for visually impaired persons. In *2021 2nd International Conference on Smart Electronics and Communication (ICOSEC)* (pp. 1102-1108). IEEE.

[SCS 16] Sennotech Co. Ltd., Shenzhen, China. (2016) ―Sennotech sensing innovative,‖Insole Smart & Natural. 2016. Available: http://www.sennotech.com/EN/product/insole.php.

[SOG 06] Song, J., & Chung, M. (2006, November). SHOES: secure healthcare oriented environement service model. In *2006 IEEE biomedical circuits and systems conference* (pp. 89-93).

[WAN 18] Wang C, Kim Y, Min SD (2018) Soft-Material-Based Smart Insoles for a Gait Monitoring System. Materials (Basel). 11 (12):2435. DOI: 10.3390/ma11122435

[WIL 13] WIISEL, (2013) ―Wireless insole for independent and safe elderly living,.Available: http://www.wiisel.eu/?q=content/documents.

[XLZ 11] Xu, W., Li, Z., Huang, M. C., Amini, N., & Sarrafzadeh, M. (2011, May). ecushion: An etextile device for sitting posture monitoring. In 2011 International Conference on Body Sensor Networks (pp. 194-199). IEEE.